(Preprint) AAS 11-216

OPTICAL NAVIGATION PLANNING PROCESS FOR THE CASSINI SOLSTICE MISSION

Simon Nolet,* Stephen D. Gillam,* and Jeremy B. Jones†

During the Cassini Equinox Mission, the Optical Navigation strategy has gradually evolved toward maintenance of an acceptable level of uncertainty on the positions of the bodies to be observed. By counteracting the runoff of the uncertainty over time, this strategy helps satisfy the spacecraft pointing requirements throughout the Solstice Mission, while considerably reducing the required imaging frequency. Requirements for planning observations were established, and the planning process itself was largely automated to facilitate re-planning if it becomes necessary. This paper summarizes the process leading to the optical navigation schedule for the seven years of the Solstice Mission.

INTRODUCTION

For such a complex mission as Cassini, it is critical to maintain an accurate knowledge not only of the orbital parameters of the spacecraft, but also of the moons to be targeted by the various flybys and observed. While most of the Titan flybys remain at an altitude of more than 950 km, flybys of small icy moons like Enceladus are regularly 100 km or less in altitude (the lowest one being 25 km).[1] At such a low altitude, the position of the spacecraft relative to the targeted moon at the time of the flyby has to be known to within only a few kilometers. Years of experience, tuning and lessons learned while flying in the Saturnian system allowed Cassini's ground-based navigation filter to gradually provide that level of accuracy.

Cassini uses two main types of measurements for navigation: radio data (Doppler and range) along the line-of-sight to the spacecraft using the Deep Space Network (DSN),[2] and optical images of the icy moons of Saturn.[3] This paper focuses on Optical Navigation (OpNav), which can be defined as the use of onboard imaging, in this case imaging of the icy moons of Saturn, to aid in the determination of the spacecraft trajectory and of the target's ephemerides.[4] OpNav has been around at JPL for a few decades already, being operational as early as the 1970's first on the Mariners and then on the Viking orbiters at Mars using Vidicon television cameras. Technological advances since then, including the invention of the charged coupled device (CCD), were made available to the engineers developing the Cassini spacecraft in the 1990's. Cassini is equipped with two main cameras: the Narrow Angle Camera (NAC) and the Wide Angle Camera (WAC). Although both are primarily scientific instruments, they can also be used for OpNav. The primary OpNav instrument is the NAC. It consists of a 1024 x 1024 pixel CCD, with an angular resolution of 6 microradians per pixel, a field of view covering 6 milliradians and a nominal focal length of 2000 millimeters. A more detailed camera model can be found in (Reference 3). Since

* Optical Navigation Engineer, Jet Propulsion Laboratory, 4800 Oak Grove Drive, M/S 230-205, Pasadena, CA 91109.
† Cassini Navigation Lead, Jet Propulsion Laboratory, 4800 Oak Grove Drive, M/S 230-205, Pasadena, CA 91109.

launch in 1997, the NAC has taken thousands of images, and remains an extremely reliable instrument to this date.

The Cassini Mission consists in fact of three mission phases: the Prime Mission from 2004 to 2008, the Equinox Mission (EM) from 2008 to 2010, and the Solstice Mission (SM), from 2010 onward. In the Prime Mission, an intense OpNav campaign was undertaken to reduce the uncertainty in the ephemerides of the moons of Saturn (main targeted bodies) as quickly as possible.[3] A similar approach was pursued when planning the OpNav observations for the EM, although the frequency of the observations was reduced.[5] However, during the EM, the Optical Navigation strategy has gradually evolved toward maintenance of ephemerides, where the goal is to maintain an acceptable level of uncertainty on the positions of the bodies to be observed. By counteracting the runoff of the uncertainty over time, this new strategy helps satisfy the spacecraft pointing requirements throughout both EM and SM. It was quickly discovered that such a strategy would also have the advantage of considerably reducing the required frequency of the OpNavs. Because the NAC is not gimbaled, the whole spacecraft has to rotate when pointing it at a given target. Only a limited amount of science can be performed when taking an OpNav. Also, during the SM, the Cassini Navigation Team was faced with the need to reduce the workforce to the minimum required level, as it is often the case with extended missions. Therefore, both reducing the frequency of OpNavs and the operational complexity, while still satisfying Cassini's pointing requirements, became very important objectives of this research. To support this objective, a set of requirements for planning observations was established, and the planning process itself was largely automated through a suite of software tools to facilitate replanning if it becomes necessary.

This paper elaborates on this new ephemerides maintenance strategy, and describes the planning process that followed. The first section covers the theoretical foundation behind that strategy. Then, the general requirements established to instantiate it are discussed, as well as the process by which these requirements were implemented. Finally, the resulting SM OpNav observation schedule is illustrated.

OPTICAL NAVIGATION IMAGING INFORMATION CONTENT

The information content of an optical navigation image has always been a critical but elusive parameter. It is critical since taking optical navigation images uses spacecraft resources and each image should, in a measurable sense, increase the knowledge of the dynamical system.

Cassini offers a unique situation where this question can be considered in a simplified environment. In particular, at the start of the SM, the spacecraft orbit is well determined by the radiometric data, the satellite ephemerides are well determined and the uncertainties are small. This situation allows for the simplification of the problem.

This section considers the question of the information content of a given image. In this context, information content is defined to be the ability of an optical navigation image to improve the uncertainty in a satellite ephemeris. The focus will be on the estimation of the down track component of the satellite ephemeris.* Analytic expressions will be derived that show that the information content is a function of the camera parameters, the orientation of the satellite motion with respect to the line of sight, the range to the satellite, the measurement uncertainty and the a priori uncertainty in the satellite down track position. The details of the phase angle and satellite

* Since the satellites are in near circular orbits in the Saturian equatorial plane, only the down track component has a secular term (or grows with time).

angular diameter will be ignored since they primarily influence the scheduling of the optical navigation images and not the accuracy.

The major result of the analysis is an estimate of the frequency of optical navigation images required to control the growth in the down track uncertainty and the expected level of uncertainty. These simplified results will be extended to the general navigation problem and used to derive requirements on other parameters proper to optical navigation.

Dynamics

Since all of the satellites are in near circular equatorial orbits, it is assumed the ephemeris runoff is in the down track direction due to uncertainty in the central body mass and the semi-major axis of the satellite orbits. The resonance between the satellites is a long period term relative to the measurement frequency and can be ignored. The runoff in the down track direction is a result of an error in the mean motion of the satellite:

$$n^2 = \frac{\mu}{a^3} \tag{1}$$

where

n – mean motion (radians/second)

μ – the gravitational constant (GM) (km^3/s^2)

a – satellite orbit semi-major axis (km)

Rearranging Eq. (1):

$$\mu = n^2 a^3 \tag{2}$$

The first order variation of Eq. (2) is:

$$\delta\mu = 2na^3\delta n + 3n^2a^2\delta a \tag{3}$$

Regrouping:

$$\frac{\delta\mu}{\mu} = 2\frac{\delta n}{n} + 3\frac{\delta a}{a} \tag{4}$$

And finally:

$$\frac{\delta n}{n} = \frac{1}{2}\left(\frac{\delta\mu}{\mu}\right) - \frac{3}{2}\left(\frac{\delta a}{a}\right) \tag{5}$$

The variation in the mean motion is a function of the variations in the central body gravitational constant and the satellite orbit semi-major axis. The growth in the down track position (δd) of the satellite can be derived from:

$$\delta\dot{d} = a\delta n = an\left(\frac{\delta n}{n}\right) = \frac{an}{2}\left(\frac{\delta\mu}{\mu}\right) - \frac{3an}{2}\left(\frac{\delta a}{a}\right) \tag{6}$$

The growth of the satellite down track position at time t can be expressed as:

$$\delta d = \begin{bmatrix} a & \frac{an}{2}t & -\frac{3an}{2}t \end{bmatrix} \begin{bmatrix} \left(\frac{\delta d_0}{a}\right) \\ \left(\frac{\delta \mu}{\mu}\right) \\ \left(\frac{\delta a}{a}\right) \end{bmatrix} \tag{7}$$

where

δd_0 – down track position variation at the initial epoch t_0

t – time from the initial epoch t_0

Measurement

An Optical Navigation image provides an estimate in the measured location of the satellite relative to the a priori location. Assuming that the error is in the mean motion, the displacement, for small values, will be along the instantaneous satellite velocity vector, as shown in Figure 1. For small angles, the measurement, in radians, is:

$$z = \frac{\sin(\alpha)}{r}\delta d \tag{8}$$

where

δd – down track variation

α – angle between the line of sight and the instantaneous satellite velocity vector

r – range from the spacecraft to the satellite

z – angle subtended by the down track variation in the camera frame

The variations, in the camera frame, are measured in pixels and, for Cassini, one pixel subtends 6 x 10^{-6} radians. Thus, in the camera frame, the measurement, in pixels, z, is:

$$\mathrm{z} = \frac{\sin(\alpha)}{k * r}\delta d + v = h\delta d + v \tag{9}$$

where

v – measurement uncertainty, assumed gaussian distribution with zero mean and variance R

k – constant, 6E-6 radians per pixel

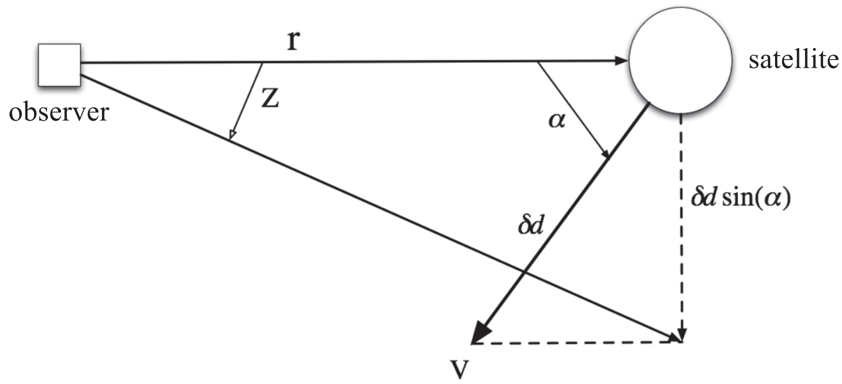

Figure 1. Optical Measurement Geometry.

Estimation

The parameters to be estimated are:

$$S = \left[\left(\frac{\delta d_0}{a} \right) \quad \left(\frac{\delta \mu}{\mu} \right) \quad \left(\frac{\delta a}{a} \right) \right] \tag{10}$$

where

δd_0 – uncertainty in down track position at the initial epoch t_0

$\delta \mu$ – uncertainty in the central body GM

δa – uncertainty in the satellite semi-major axis

Prior to a measurement, the covariance of the state is:

$$\mathrm{E}\left\{ SS^T \right\} = \sigma_s^2 = \begin{bmatrix} \left(\frac{\sigma_{d_0}}{a} \right)^2 & 0 & 0 \\ 0 & \left(\frac{\sigma_\mu}{\mu} \right)^2 & \rho \left(\frac{\sigma_\mu}{\mu} \right) \left(\frac{\sigma_a}{a} \right) \\ 0 & \rho \left(\frac{\sigma_\mu}{\mu} \right) \left(\frac{\sigma_a}{a} \right) & \left(\frac{\sigma_a}{a} \right)^2 \end{bmatrix} = M \tag{11}$$

The a priori uncertainty in the central body GM and the satellite semi-major axis are taken from the satellite ephemeris estimation and are highly correlated. The estimation of these parameters is assumed to be independent of the local optical image processing; therefore, the down track uncertainty is assumed to be uncorrelated with the other parameters.

After the measurement, the optimal estimate of the state covariance is given by:[6]

$$P = M - MH^T \left(HMH^T + R \right)^{-1} HM \tag{12}$$

where

R – the variance of the measurement uncertainty $\nu\left(\mathrm{E}\left\{\nu^2\right\}\right)=\sigma_m^2$

H – determined by Eq. (13)

$$H = \frac{\sin(\alpha)}{k*r}\left[a \quad \frac{an}{2}t \quad -\frac{3an}{2}t\right] = h\left[a \quad \frac{an}{2}t \quad -\frac{3an}{2}t\right] \tag{13}$$

Simplification

In order to gain an insight into the estimation process, consider only the down track portion of the update equation, Eq. (11):

$$\begin{aligned}\left(\sigma_{d_0}^{+}\right)^2 &= \left(\sigma_{d_0}^{-}\right)^2 - \left(\left(\sigma_{d_0}^{-}\right)^2 h\right)^2\left(\frac{1}{h^2\left(\sigma_{d_0}^{-}\right)^2+\sigma_m^2}\right) \\ &= \left(\sigma_{d_0}^{-}\right)^2\left[1-\frac{1}{1+\left(\dfrac{\sigma_m}{h\sigma_{d_0}^{-}}\right)^2}\right]\end{aligned} \tag{14}$$

where

$\sigma_{d_0}^{+}$ – the down track uncertainty at the initial epoch t_0, after the measurement

$\sigma_{d_0}^{-}$ – the down track uncertainty at the initial epoch t_0, before the measurement

σ_m – the measurement uncertainty

h – partial of the measurement equation, Eq. (9)

If we define an intermediate variable f as the weighted ratio of the measurement uncertainty and the down track uncertainty:

$$f = \frac{\left(\dfrac{\sigma_m}{h}\right)}{\sigma_{d_0}^{-}} = \frac{\left(\dfrac{k*r}{\sin(\alpha)}\right)\sigma_m}{\sigma_{d_0}^{-}} \tag{15}$$

then Eq. (14) can be reduced to:

$$\left(\sigma_{d_0}^{+}\right)^2 = \left(\sigma_{d_0}^{-}\right)^2\left[\frac{f^2}{1+f^2}\right] \tag{16}$$

Now, consider the following two cases:

$f >> 1$:

In this case the scaled measurement uncertainty, σ_m/h, is greater than the a priori down track uncertainty at the initial epoch t_0, $\sigma_{d_0}^-$, and Eq. (17) can be used to approximate Eq. (16). There is no improvement from taking the measurement.

$$\left(\sigma_{d_0}^+\right)^2 \approx \left(\sigma_{d_0}^-\right)^2 \left[\frac{f^2}{f^2}\right] = \left(\sigma_{d_0}^-\right)^2 \tag{17}$$

$f << 1$:

Eq. (16) can be expanded in a series:

$$\left(\sigma_{d_0}^+\right)^2 = \left(\sigma_{d_0}^-\right)^2 f^2\left[1 - f^2 + f^4 \ldots\right] \tag{18}$$

Therefore, to first order:

$$\sigma_{d_0}^+ = \sigma_{d_0}^- f = \frac{\sigma_m}{h\sigma_{d_0}^-}\sigma_{d_0}^- = \frac{k * r}{\sin(\alpha)}\sigma_m \tag{19}$$

Thus if f is much less than 1, the uncertainty in the down track depends only on the geometry and the measurement accuracy.

Results

The fundamental result of this analysis is that the information content in the OpNav image measurement is $\frac{k * r}{\sin(\alpha)}\sigma_m$. Since for a given camera k is a fixed parameter (6 x 10^{-6} radians per pixel for Cassini), the uncertainty in a single measurement is a function of the range, the magnitude of the ephemeris error normal to the line of sight and the uncertainty in the center finding. For instance, at a range of 1 million kilometers, a measurement uncertainty of 0.5 pixels results in a down track uncertainty of 3 km normal to the line of sight. The current satellite ephemeris uncertainties, other than Titan and Enceladus, are on the order of 3 to 7 km, which suggests that the measurement uncertainty is on the order of 0.5 pixels.

The analysis further suggests that at the current levels of uncertainty, additional optical navigation images will have little or no effect unless the range to the satellite is small, which can introduce other problems. The down track uncertainty is expected to increase as a result of the uncertainties in the Saturn GM and the Satellite semi-major axis. The radial and out-of-plane uncertainties would be expected to increase due to third body perturbations, but this growth should be small relative to the growth in the down track direction. In order to restrain the growth in the down track uncertainty, periodic measurements of the satellite position are required.

To quantify the results of this simplified analysis, an epoch state filter was developed using the above formulation.[6] The filter assumed the current uncertainties in the satellite state, satellite semi-major axis and Saturn GM. Semi-major axis and GM are correlated. The simulation allowed the other parameters to be investigated.

Figure 2 presents the time history on one particular simulation. The upper thin black line represents the predicted uncertainty without any optical navigation images (and no close flybys). For Mimas the initial uncertainty is about 3 km and, using the simplified model, is predicted to increase to about 40 km in 5 years. The black star pattern represents the uncertainty assuming that a Mimas image is taken every 180 days. The uncertainty increases until the image is taken and the down track uncertainty is updated. The red stars represent the uncertainty right after the image is taken. The simulation assumes that the parameters controlling the growth rate (Saturn GM and satellite semi-major axis) are not improved.

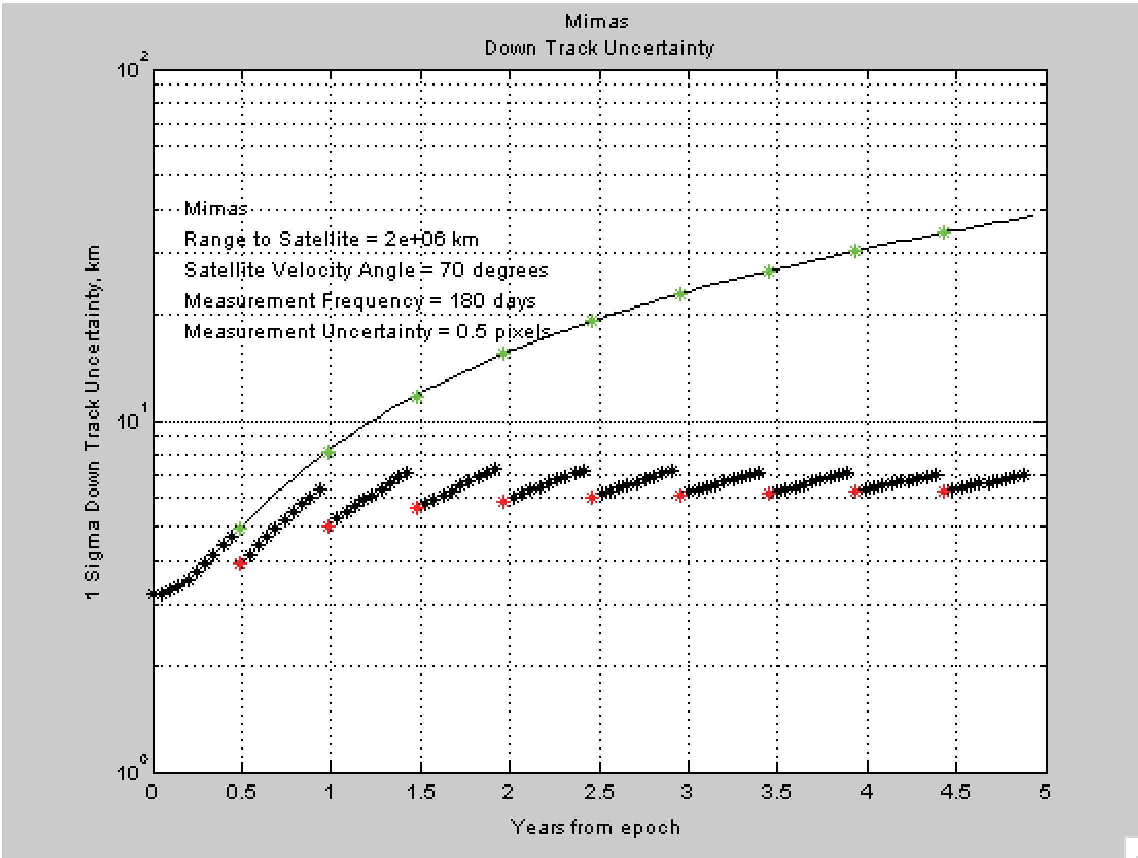

Figure 2. Simulation of Mimas Down Track Ephemeris Uncertainty.

Figure 3 presents predicted uncertainty in the Mimas down track position at the end of the simulation, as a function of the measurement frequency (the time between measurements) and the measurement range. This is the uncertainty just prior to the measurement. The measurement uncertainty is 0.5 pixels and the velocity angle is 70 degrees. As may be seen from the figure, the uncertainty is a strong function of the measurement range and only weakly dependent on measurement frequency. At a measurement range of 2 million kilometers, increasing the measurement frequency from 50 days to 300 days resulted in degradation from about 6.5 km to about 7.5 km. A factor of 1.1 increase in down track position uncertainty resulting from a factor of 6 decrease in measurement frequency.

Discussion

Several general conclusions can be made as a result of this analysis. First, while this analysis focuses on the down track component of the uncertainty, each OpNav image provides information in the two directions normal to the line of sight. Therefore each OpNav will provide information on the radial and out-of-plane component. This should limit any growth in these directions.

Second, this is a relative position problem and not an absolute position problem. In order to simplify the analysis, the spacecraft position uncertainties were assumed to be very small relative to the satellite position uncertainties. This allows all of the information in the images to be applied to the satellite ephemeris. If, however, the situation was reversed and the satellite uncertainties were small relative to the spacecraft uncertainties, then the information would be used to decrease the spacecraft uncertainties.

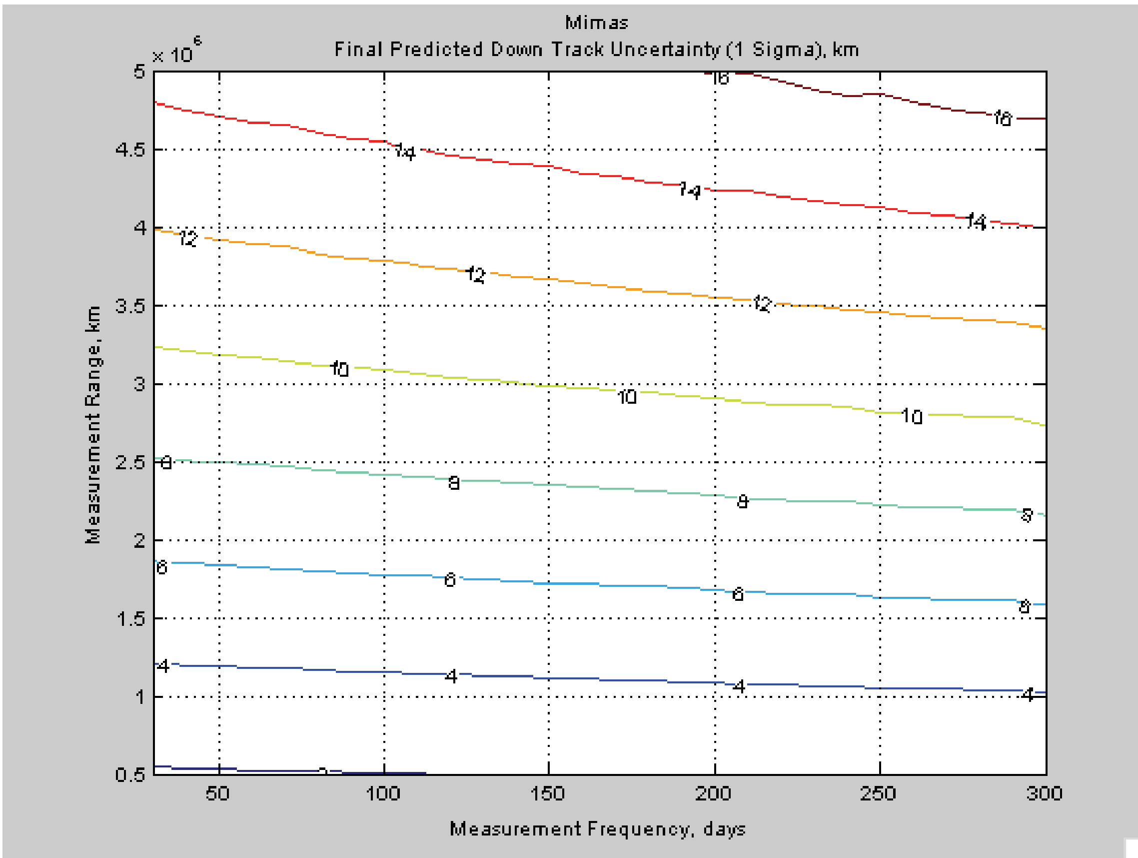

Figure 3. Mimas Predicted Down Track Uncertainty as a function of Measurement Frequency and Measurement Range.

The epoch state filter developed using the formulation presented in this section can be used to perform sensitivity analysis to study the effect of certain parameters on the overall ephemerides uncertainty. This was the approach taken to derive the Navigation requirements, which is discussed in the next section.

ELABORATION OF THE REQUIREMENTS

The elaboration of the OpNav planning process was guided by a set of requirements. These requirements can be divided into three categories: navigation requirements, picture processing requirements and planning requirements. Some requirements were derived using a simplified formulation to estimate the level of uncertainty on the ephemerides of the moons of Saturn. Others were simply based on experience. Each category is discussed in details below.

Navigation Requirements

The Navigation requirements are related to navigation accuracy. The proposed Cassini pointing requirement during the SM has been established as being able to predict the pointing to the major Saturnian satellites to an accuracy of 1 milliradians (1-σ) when the range to the satellites is greater than 20,000 km. In the worst case, when the closest range is 20,000 km, this requirement translates to an ephemeris accuracy of 19.4 km, assuming a conservative 5 km Saturn-relative spacecraft uncertainty (1-σ). Also, the uncertainty on the ephemerides has to be low enough to ensure the safety of the spacecraft during the low altitude encounters. Therefore, an extensive study was performed to determine the set of requirements that provides sufficient conditions to maintain the uncertainty on the ephemerides at an acceptable level. For a given satellite, the level of uncertainty is acceptable if:

1. The Cassini pointing requirement is met, and
2. The 1-σ uncertainty remains below 20% of the altitude at closest approach.

A required ephemeris accuracy was determined for each satellite for the SM. It is based on the worst of the two conditions mentioned above. An epoch state filter, using the formulation presented in the previous section, was designed to simulate the processing of OpNavs and their effect on the ephemerides uncertainty. Simulations were run where the inputs to the filter were varied to analyze the sensitivity of the uncertainty to each. Four parameters were selected for the analysis: maximum range, minimum image frequency, velocity angle range and maximum measurement uncertainty. These parameters were relaxed as much as possible, until increasing any of them would cause the level of uncertainty to exceed the acceptable limit. This approach, applied to each satellite, led to the recommendations shown in Table 1.

Table 1. Minimum Optical Image Parameter Recommendations.

Satellite§	Max Range, km	Min Image Frequency, per year	Velocity Angle Range, deg	Max Measurement Uncertainty, pixels
Mimas	2.5 e6	1	30-150	1
Enceladus	2.5e6	1	30-150	1
Tethys	3e6	1	30-150	1
Dione	3e6	1	30-150	1
Rhea	2.5e6	1	30-150	1
Hyperion	2.6e6	1	30-150	1
Iapetus	3e6	.5	30-150	1

For simplicity sake, the results in Table 1 were generalized into the following four Navigation requirements, to ensure the required level of uncertainty for each satellite:

- The range to the satellite has to be less than 2.5 million kilometers.
- The angle between the velocity vector of the satellite and the camera boresight has to be between 30° and 150°.

§ Titan is not included in the list because there is adequate ephemeris knowledge maintained with radiometric data via frequent flybys. Also, Titan's atmosphere makes is very difficult to get accurate centroid measurement accuracy.

- The frequency of OpNavs has to be at least one per year (one every two years for Iapetus).
- The centroid measurement accuracy has to be better than 1 pixel.

The first two requirements are directly verified in software using JPL-developed software tools that provide the position and velocity over time of Cassini and the major Saturnian bodies. To provide a margin for the possible loss of pictures, the frequency of OpNavs is double the third requirement. There are a total of seven bodies to observe. With two pictures per body, but one for Iapetus, the total number of required OpNavs per year is thirteen. With on average 20 revolutions per year throughout the SM, it was convenient to organize the observations on a per revolution basis. More specifically, one OpNav is requested per apoapsis period*, outside of periods of critical science activities which tend to concentrate near periapsis. Each apoapsis period is dedicated to a specific body. To provide the science planning leads with more options when planning spacecraft activities, a total of three observation windows meeting all the requirements are provided for each apoapsis, and the leads are given the freedom to select the one they feel is the most convenient for them. The result of this implementation process is one OpNav of the intended target per apoapsis, with a few empty apoapsis periods each year when viewing geometries are not favorable. This strategy also meets the desire to spread out OpNavs over time instead of putting them all in one or two sequences per year, to maintain the expertise between the different team members.

The fourth requirement was approached differently. Since the accuracy of the OpNav centroid finding techniques depends on the quality of the picture being analyzed, it is hard to predict what it will be. However, after many years of experience, it was observed that when the picture processing requirements described below are met, the accuracy of the OpNav centroid finding techniques is well under 1 pixel, more on the order of 0.25 pixel.

Picture Processing Requirements

OpNavs provide to the Orbit Determination (OD) filter the measured centroid of the body being observed. As in the EM, a set of requirements was established to ensure accurate processing of each picture by the OpNav software tools. The accuracy is affected by the lighting conditions and the ability to distinguish the satellite from the background of the picture. Therefore, a set of requirements has to address geometric events like occultations and eclipses. The phase angle and the apparent size of the satellites in the picture frame are also important criteria. The following list of picture processing requirements was determined largely based on experience working with the OpNav software:

- The phase angle should be less than 140° for accurate centroiding.
- The satellite should be more than 1.5 times the Narrow Angle Camera (NAC) field of view from Saturn's limb (9.2 mrad), to prevent image contamination by Saturn's light.
- The satellite should be separated (in the picture) from the Rings (up to F-Ring).
- The satellite should be outside the shadow cast by Saturn and the Rings (up to F-Ring).
- The satellite apparent diameter in the camera frame should be between 20 and 350 pixels for accurate centroiding.
- A minimum of two stars must be present in the picture to provide twist† information.

---

* An apoapsis period is defined as a period of time in Cassini's orbit when the distance to Saturn Barycenter is over 18 Saturn radii (RS), and over 25 RS between for the period spanning July 2013 to January 2014, when the semi-major axis of Cassini is raised.
† Roll around the camera boresight.

These requirements are verified using JPL-developed navigation software tools that provide the position and velocity over time of Cassini, the major Saturnian bodies, Saturn and the Sun. These software tools expanded on software developed during the Prime Mission. The satellite apparent diameter requirements were translated into maximum and minimum range requirements for each of the satellites. The shadow and separation requirements were verified using range information and angular separation between the relevant bodies. The minimum star requirement was verified with the same star catalogs as the ones used by Cassini's OD filter.

Planning Requirements

Because of the need to keep the workforce to a minimum during the SM, the Navigation team has come up with a planning process that eliminates the interaction with the science planning process. For this process to be successful, the science planning leads have set up the following planning requirements to ensure the scheduling of OpNavs outside periods of high contention for observing time, or outside periods when the spacecraft remains Earth-pointed:

- The OpNavs must be inside apoapsis periods.
- The OpNavs must be outside a period of ±1 day around each flyby.
- The OpNavs must be outside downlink windows.
- The OpNavs must be outside solar conjunction periods, defined by a Sun-Earth-Probe (SEP) angle less than 3°.

The first two requirements are verified with the same software tools described above. The flyby and downlink avoidance requirements were simply implemented as exclusion time zones. During solar conjunction periods, all spacecraft activities are reduced to a minimum. The high gain antenna remains Earth-pointed during that time.

Ultimately, the software tools described above provide the OpNav analyst with a list of possible observation windows meeting all requirements, for each satellite, sorted by apoapsis period. They also provide charts indicating the availability of stars during the selected windows. It is left to the analyst to select which satellite to observe at each apoapsis period, and to select the three observation windows per apoapsis to add to the schedule. This process is described in more details in the next section.

SCHEDULING PROCESS

As it is the case when extending any flight mission, the Cassini Navigation Team was expecting a reduction of personnel for the SM. To facilitate replanning with the reduced workforce, the scheduling process has been almost entirely automated. Most of the requirements presented in the previous section were coded into scripts, which were called at different stages of the process. The requirements related to orbital dynamics and geometric constraints (OpNavs constrained to apoapsis periods, minimum and maximum range to the target, *etc*.) were verified using JPL-developed navigation software and the ephemeris files used to plan the SM. Other requirements were coded as time exclusion zones around predetermined time periods, like predicted downlink windows and flybys. Only the centroiding accuracy requirement was not coded, since it is believed to be always lower than 0.5 px, probably more around 0.25 px.

Each of the seven years of the SM was planned year-by-year as following. Each year was discretized into 80,000 time intervals, ~400 seconds each in duration. The start of a time interval is referred to as a data point. All of the requirements were verified at each data point, for every satellite. The result of this first phase of the process is a list of available windows* for every satellite, sorted by apoapsis period.

The next step is to associate a satellite for each apoapsis period. In doing so, it is a good practice (although not a requirement) to proceed in the following order:

1. OpNavs approximately 2 months before a flyby of the corresponding satellite,
2. Iapetus and Hyperion, since they are available only a few periods per year,
3. Mimas and Enceladus next, especially for periods of low inclination, to maximize their placement windows,
4. Tethys, Dione and Rhea last, since they are the easiest to assign.

Once a satellite was assigned to each apoapsis period, the analyst selects up to three windows per period for the corresponding satellite. Since eventually the science planners are going to select only one OpNav per apoapsis period, this technique ensures that the OpNav selected for that period will be one intended by the analyst. Windows should be selected primarily based on duration. The longer a window is, the more flexibility the science planners will have when scheduling the OpNav in that window. Also, the three selected windows should be spread out over the apoapsis period, again to provide more flexibility.

Next, the predicted number of stars in the picture frame has to be at least two for the whole duration of the windows selected in the previous step. This process is more computationally intensive. Each of the three windows is discretized into 5 minute intervals. The software then simulates the picture frame the NAC would see at that time, and counts the number of stars with magnitude between 7 and 11, the interval generally providing good results. The software is also capable of slightly moving the camera orientation with the hope of seeing more stars. If less than two stars are available for part of that window period, the window is shrunk accordingly, or the analyst goes back to the previous step and selects another window.

Finally, the last step of the process is to generate, archive and publish the software products required by the science planners. The analyst runs through this entire process once for every year of the SM. This process would have to be repeated only if Cassini's reference trajectory changes, which is nominally expected only once every two years.

OBSERVATION SCHEDULE

This section provides the complete list of OpNav opportunities. Figure 4 shows a timeline summary of all the OpNavs over the SM. For each apoapsis period, two to three windows are mentioned†, from which the science planning leads will select the one that fits their schedule best. Although the proposed schedule spans the SM up to September 2016, only the first two years will probably be implemented as is. Future modifications to the reference trajectory are likely to affect the schedule, as may potential lessons learned as this new process progresses. The schedule currently ends in September 2016 (end of fiscal year). OpNavs are not anticipated to be needed for the terminal phase of the mission (flying into Saturn).

---

* Periods of time at least 90 minutes long when all the requirements are satisfied.

† The windows in the same apoapsis period cannot be distinguished from each other on the plot, which spans multiple years.

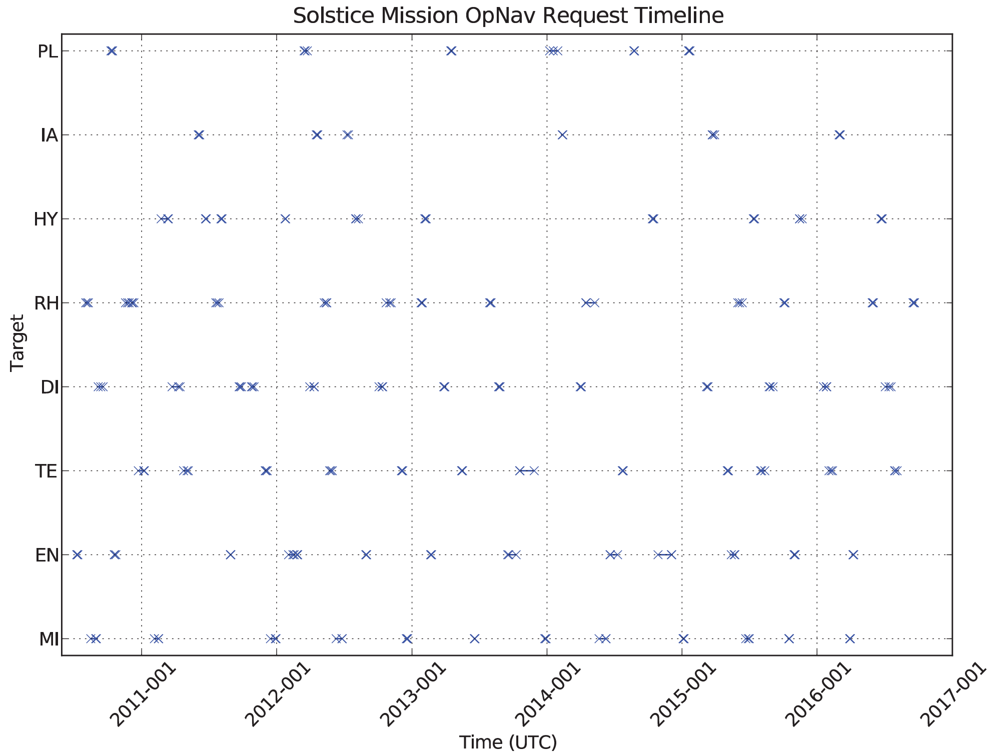

Figure 4. Timeline Summary of the OpNav Observations for the Solstice Mission.

CONCLUSION

For Cassini, the main purpose of taking OpNav images is to improve first, then maintain the knowledge of the ephemerides of Saturn's icy moons. A minimum knowledge is required to ensure accurate pointing of the instruments when observing these moons. However, because Cassini's camera is not gimbaled, the amount of science that can be performed while taking OpNav images is limited. And with the need to keep the workforce to a minimum during the SM, it is highly desirable to minimize the number of OpNavs while maintaining the ephemerides and ensuring sufficient pointing accuracy.

This concept is the main driver behind the OpNav planning process for Cassini's SM. This paper introduces the theoretical background behind the Navigation requirements established to direct the planning process. Picture and planning requirements derived from previous experience are also presented. The largely automated process by which these requirements were implemented and verified is explained in detail. Finally, the resulting OpNav schedule for the whole SM is illustrated. The general ideas behind the OpNav planning process presented in this paper are applicable to future orbiting missions at well.

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. The authors would like to acknowledge the JPL Cassini Navigation Team for their support and insights in developing and implementing the planning process presented in this paper.

REFERENCES

[1] K.E. Criddle, *et al.*, "Cassini Orbit Determination: Challenges and Triumphs Presented by Close Flybys of Enceladus." AAS paper 09-017, 32nd Annual AAS Guidance and Control Conference, Breckenridge, Colorado, 2009.

[2] P.G. Antreasian, *et al.*, "Orbit Determination Process for the Navigation of the Cassini-Huygens Mission." AIAA paper 2008-3433, SpaceOps 2008 Conference, Heidelberg, Germany, 2008.

[3] S.D. Gillam, *et al*., "Optical Navigation for the Cassini/Huygens Mission." AAS paper 07-252, AAS/AIAA Astrodynamics Specialist Conference, Mackinac Island, Michigan, 2007.

[4] W.M. Owen, *et al*., "A Brief History of Optical Navigation at JPL." AAS paper 08-053, 31st Annual AAS Guidance and Control Conference, Breckenridge, Colorado, 2008.

[5] S.D. Gillam, R. Ionasescu and P. Williams, "The Planning of Optical Navigation Pictures for the Cassini Extended Mission." AAS paper 08-241, AAS Spaceflight Mechanics Meeting, Galveston, Texas, 2008.

[6] A.E. Bryson and Y. Ho, *Applied Optimal Control*, Blaisdell Publishing Company, 1969.